The mathematical models of hyperbaric facility ventilation

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Abstract

The paper presents the theoretical models of thermal comfort and ventilation of the hyperbaric facilities. Based on the heat balance of the human body and two basic comfort conditions the comfort equation was derived for the hyperbaric environment. The comfort equation allows to determine the comfort temperature as the function of the principal environmental variables. The comfort charts for the different breathing gases are presented. The models of the continuous and interrupted hyperbaric facility ventilation are considered.

1 Introduction

The most deep diving experience is based on the breathing gas containing helium as the diluent gas, that causes certain problems with dangerous cooling of the diver. Due to the high thermal conductivity of helium, six times that of air. The comfort temperature in helium-oxygen atmospheres should be maintained at the higher level, Reimers [5], Shilling & Werts & Schandelmeier [6], $t=30$–$36^\circ$C, than that in normobaric air environment, because at increased pressure heat transfer properties of helium are accenuated; also toxic effects of contaminants are increased, for example; Shilling & Werts & Schandelmeier [6], 1% CO$_2$ breathed at about 40 m of sea water would have the same physiological effect as 5% CO$_2$ breathed at the surface of the sea. Working with compressed mixed gases greatly complicates the problems of control and the maintenance of the hyperbaric environmental parameters. In the design of the hyperbaric facilities ventilation and conditioning systems safety factors are extremly important.

One of the major tasks for the life support systems of the hyperbaric facility is to create an environment which maintains a proper level of oxygen partial
pressure, temperature, humidity and consequently thermal comfort and possibility of safety respiration for the divers.

The hyperbaric facilities are used for support of the saturation diving; there are two general types of the hyperbaric facilities; the sea-going deep dive systems and experimental land-based hyperbaric chambers. Our paper will focus on the thermal comfort and the theoretical ventilation models for the land-based hyperbaric chamber. The hyperbaric chamber will accommodate divers at varying pressure to simulate depth inside the chamber while external pressure remains constant (barometric pressure). One or more of these chambers constitute a land-based research centre in which man's reactions can be studied and carefully monitored by a personnel who are not themselves exposed; Shilling & Werts & Schandelmeier [6].

A large number of papers concerned with thermal comfort and the hyperbaric ventilation systems have been presented. Most of these papers are experimental and limited to special experimental diving activities and they cannot be generalized. Some theoretical papers presented very simple models which are not sufficient to describe all problems related to the wide variability of the hyperbaric environment.

The purpose of presented paper is to derive the hyperbaric comfort equation based on the heat balance and two basic comfort conditions. The comfort equation allows to determine the comfort temperature inside the hyperbaric chamber as the function of the most important environmental parameters. The paper is aimed at deriving theoretical models of the continuous and interrupted ventilation which enable to determine ventilation rates required for removal of contaminants.

2 The mathematical models of the hyperbaric facilities ventilation

The ventilation systems of the hyperbaric facilities should provide for maintaining safe level of oxygen, thermal comfort and removal of carbon dioxide, and the other contaminants. The rate of ventilation depends upon the number of the divers, their level of activity, and the breathing gas being used.

In order to determine ventilation rates and total gas requirements it is necessary to develop the theoretical models of the hyperbaric facilities ventilation. A choice of the proper model of ventilation is very important for designing the ventilation systems of the hyperbaric facilities.

2.1 The continuous ventilation

Removal of the contaminants from the hyperbaric atmosphere is presented as the example of carbon dioxide removal which is exhaled inside the facility. The method is based on the assumption that emission of carbon dioxide is equal to the oxygen consumption, and that the amount of the consumed oxygen, and the amount of ventilating gas are related to standard pressure. The streams of the
consumed oxygen and the ventilating gas are assumed to be independent on the depth (in fact there is a small dependence on the depth, Brennan & Bdonchuk [1]).

The molar balance of carbon dioxide for the hyperbaric facility is given as:

$$\frac{pV_k}{RT} \frac{dx}{dt} = \frac{p_o}{RT} (\dot{V}x_w + k\dot{V}) - \frac{p_o}{RT} \dot{V}$$

(1)

Then integration gives:

$$x(t) = x_w + \frac{k\dot{V}}{V} = x_w + \frac{k\dot{V}}{V} + \left( x_o - x_w - \frac{k\dot{V}}{V} \right) \exp \left( \frac{-p_o}{p} \frac{\dot{V}}{V_k} \frac{t}{\tau} \right)$$

(2)

Eqn (2) gives the instantaneous molar fraction of carbon dioxide inside the hyperbaric facility. Introducing to eqn (2) $\tau \to \infty$ gives:

$$x(\infty) = x_w + \frac{k\dot{V}}{V}$$

(3)

It is more convenient to change eqn (3) to a partial pressure form. Then eqn (3) becomes:

$$\dot{V} = k \frac{p\dot{V}}{\bar{p} - p_w}$$

(4)

Eqn (4) describes the continuous ventilation for the flushing gear such as the traditional diver's helmet supplied with the gas from the surface.

Eqn (2) enables to determine the continuous ventilation rate for the hyperbaric chamber. Despite the physiological advantages, the continuous ventilation is not commonly used because of technical difficulties and noise discomfort. The continuous ventilation system is used in the hyperbaric chambers with an external gas regeneration systems and for the classic diver's helmets.

2.2 Interrupted ventilation

Interrupted ventilation is used in the hyperbaric facilities with an open circuit ventilation. The internal atmosphere of the hyperbaric chamber is pressurized with the breathing mixture to the required pressure. During the time required to reach the required depth of diving the hyperbaric chamber may be not ventilated. The time since the beginning of the diver's compression to the beginning of the ventilation is called "time to the first ventilation". The theoretical model of interrupted ventilation is presented as the example of carbon dioxide removal. Based on the molar balance of carbon dioxide in unventilated space of the hyperbaric chamber, the following eqn can be written:

$$x(\tau) = x_o + k \frac{p_o\dot{V}}{pV_k} \tau$$

(5)

Eqn (5) describes the instantaneous molar fraction of carbon dioxide in unventilated space.

Substitution to eqn (5) the permissible partial pressure of carbon dioxide:
and conversion of eqn (5) gives:
\[
\tau^{(1)} = \frac{V_k}{kV} \frac{p_{\text{max}} - px_o}{p_o}\]

Eqn (7) enables to determine "time to the first ventilation".

Let's assume that mean rate of oxygen consumption is
\(\dot{V} \approx 0,8 \text{dm}^3 / \text{min} = 1,33 \cdot 10^{-5} \text{m}^3 / \text{s}\) (for the resting diver and a physician) and the permissible partial pressure of carbon dioxide is \(p^* = 1,5 \text{kPa}\).

"The time to the first ventilation" is determined from eqn (7) as:
\[
\tau^{(1)} = 20 \frac{V_k}{k} \quad [\text{min}]
\]

The intensity of interrupted ventilation is determined from eqn (2) on assumption that the emission of contaminant is relatively small compared to the amount of the ventilating gas. The amount of the ventilating gas related to standard pressure \(P = p_o\) is given by:
\[
V = \dot{V} \tau = \frac{P}{p_o} V_k \ln\frac{x_o - x_w}{x_k - x_w} \quad \text{for} \quad k\dot{V} \ll \dot{V}
\]

Interrupted ventilation should be performed in the shortest time as possible. The time to the next ventilation should be determined from eqn (7) substituting for \(x_w, x_k\) from eqn (9).

Presented models of the continuous and interrupted ventilation are based on the assumption of the complete miscibility of the gases.

Now, our studies are focused on experimental verification of presented models of ventilation.

### 3 Thermal comfort

During steady state, the thermoregulation system of the body maintains its temperature by striking a balance between heat generation and dissipation. The overall thermal balance of the human body is expressed, according to Fanger [2], with the following equation:
\[
\dot{Q} - \dot{Q}_a - \dot{Q}_c - \dot{Q}_w - \dot{Q}_d = \dot{Q}_p + \dot{Q}_c + \dot{Q}_d
\]

Based on eqn (10) and two basic comfort conditions related with the heat loss by water evaporation, Kozak & Majchrzycka [3] and the mean skin temperature as the function of the level of activity; Fanger [2], the comfort equation has been derived, Majchrzycka [4].

The comfort equation for the hyperbaric environment is given by:
\[
\dot{q}_M \geq 2 \cdot 10^{-7} q_M (5622 - 4 \cdot 10^{-9} (Rc_p)^{-1} p\dot{q}_M (35 - t)) - \\
\bigg\{1,27 \cdot 10^{-9} \beta_a^{-1} + w\bigg(\dot{p}_s - \dot{p}_{sw}\bigg) \beta F_{pcf} r = (8925 - 6,5q_M - 250E) I_{cf} \lambda = \\
= 4 \cdot 10^{-8} f_c^a (T_{cf} - T_r^a) + \alpha f_c^a (t_{cf} - t)
\]
The thermal properties of the breathing gas should be determined according to, Sobański [7]. The comfort equation allows to determine for each type of the diver's activity and the type of clothing all the combinations of the temperature, humidity, the gas velocity, the mean radiant temperature which will create thermal comfort inside the hyperbaric chamber filled up with the gas mixture of the assumed composition and the total pressure. The comfort equation was solved for the different breathing mixtures: \( O_2 + He; O_2 + He + N_2;\) \( O_2 + H_2; O_2 + He + CO_2 + SF_6;\) within the total pressure range \( p = 1 \div 6\, MPa;\) activity level of the diver \( \dot{q}_M = 58 \div 123\, W/\text{m}^2;\) humidity \( \varphi = 0.4 \div 1;\) relative gas velocity \( v = 0 \div 0.3\, m/s;\) the mean radiant temperature \( t_r = 0 \div 50^\circ C;\) the clothing insulation \( I_d = 0.37 \div 1.1\, clo.\)

The solutions of the comfort equation are presented in the comfort charts, which show comfort lines (the mean radiant temperature versus the comfort temperature with the gas velocity as the parameter).

In Fig 1 and Fig 2 the comfort lines are shown for the breathing mixtures \( O_2 + He;\) \( O_2 + He + CO_2 + SF_6.\) The comfort lines cross each other where the gas temperature is equal to the temperature of the outer surface of the clothing. At that point, the heat transfer will be independent on the gas velocity. The comfort temperature in the hyperbaric environment increases with the total pressure of the gas and depends on the type gas and must be maintained at the higher level than that in normobaric air environment.

Fig 1. The comfort lines for \( O_2 + He, p = 1\, MPa; I_d = 0.37\, clo;\)
\( \dot{q}_M = 58\, W/\text{m}^2; \varphi = 60\%.\)
According to Reimers [5], the comfort temperature in the hyperbaric environment is $t = 15 \pm 35^\circ C$, higher temperatures $t = 15 - 49^\circ C$ being encountered on compression, for helium-oxygen the comfort zone is exceptionally narrow $t = 29 \pm 32^\circ C$.

Although the comfort temperatures were determined from the theoretical comfort equation, the values obtained for helium-oxygen mixtures have confirmed the values presented by Reimers [5]. In order to simplify the determination of the comfort temperature it was therefore decided to use the regression analysis for the solutions of the comfort equation. The comfort temperature can be computed directly from the simple regression equation:

$$ t = f(p, x, \dot{q}_M, l_c, \varphi, \nu, t_r) $$

(12)

The regression functions will be presented at the Conference. The comfort equation is derived on the basis of the theory and should be experimentally verified. Now, our studies are focused on experimental determination of some parameters which occur in the comfort equation (11).
4 Conclusions

- The theoretical models of the continuous and interrupted ventilation of the hyperbaric facilities were discussed.
- Since the presented models of ventilation were derived on the assumption of the complete miscibility of the gases, an experimental verification of the ventilation models is needed.
- In our research, we started an experimental verification of the interrupted ventilation of the hyperbaric facilities during saturation diving. Researches on the ventilation of the hyperbaric facilities are continued with good results.
- The comfort equation for the hyperbaric environment has been derived on the base of the heat balance and basic thermal comfort conditions. The comfort equation allows to determine the comfort temperature as the function of the following principal variables: humidity of gas, mean radiant temperature, activity level of the diver, insulation of the clothing, relative gas velocity, the composition and the total pressure of the breathing gas.
- After experimental verification, the comfort equation will be very useful both in designing and in operating the life support systems of the hyperbaric chambers.

Nomenclature

- $c_p$ - specific heat capacity at the constant pressure, J/kg K,
- $f_{cl}$ - the ratio of the surface area of the clothed body to the surface area of the nude body,
- $F_{pcf}$ - moisture permeation factor,
- $I_{cl}$ - insulation value of the clothing, clo,
- $k$ - the number of divers,
- $p$ - the total pressure of the breathing gas, Pa,
- $p_{\text{max}}$ - the permissible partial pressure of carbon dioxide, Pa,
- $p_0$ - the standard pressure, Pa,
- $p_s$ - the saturated water pressure at the skin temperature, Pa,
- $p_{\text{sw}}$ - the partial pressure of water vapor at ambient temperature, Pa,
- $\dot{q}_M$ - the activity level of the diver, W/m$^2$,
- $\dot{Q}$ - internal heat production in the human body, W,
- $\dot{Q}_c$ - the flux of heat loss by convection, W,
- $\dot{Q}_d$ - the flux of heat loss by water vapor diffusion through the skin, W,
- $\dot{Q}_e$ - the flux of evaporative heat loss, W,
- $\dot{Q}_f$ - the flux of dry respiratory heat loss, W,
- $\dot{Q}_p$ - the flux of heat transfer from skin to outer surface of clothed body, W
- $\dot{Q}_r$ - the flux of heat loss by radiation from outer surface or the body, W,
- specific latent heat of vaporization, J/kg,
- individual constant of the breathing gas, J/kg K,
- the comfort temperature, °C, K,
- the temperature of the outer surface of the clothing, °C, K,
- mean radiant temperature, K,
- rate of oxygen consumption, m³ / s,
- rate of the fresh ventilating gas, m³ / s,
- the volume of the fresh ventilating gas related to standard pressure, m³,
- the volume of the ventilated space, m³,
- the skin wetness
- the final molar fraction of carbon dioxide,
- the initial molar fraction of carbon dioxide,
- the molar fraction of carbon dioxide in the ventilating gas,
- the instantaneous molar fraction of carbon dioxide,
- convective heat transfer coefficient, W / m² K,
- the coefficient of water evaporation in the hyperbaric environment, in normobaric air environment, kg / m² s Pa,
- the relative gas velocity, m/s,
- relative humidity of the gas,
- thermal conductivity of the gas, W/m K,

References

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